Preparation of specimens for standard tensile testing of plastic materials for FDM 3D printing

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Abstract: *Additional manufacturing (AM), commonly known as 3D printing, exists for 40 years, still evolving and improving. AM has gained great popularity in modern industries due to many advantages concerning conventional manufacturing technologies. Consequently, AM is one of nine pillars of the currently dominating industry trend – Industry 4.0. Initially, AM was mostly used for making models. Now, objects made by AM technologies, often are physical parts ready to be used as final products or to be installed as parts of assemblies in more complex systems. Because of that, in more applications, the mechanical properties of these parts have to be known for the purpose to determine load carrying capacity essential for their functionality. Mechanical properties are being tested using appropriate methods, specimens, and equipment. In order to obtain comparable and evaluable test results, the test procedures and means should be standardized. Therefore, there was a need to develop standards for testing materials used for AM. International standardization in the field of AM started 10 years ago. The international body for standardization ISO developed and published a certain number of standards, but this is just beginning. This paper discusses aspects of AM standardization in the field of testing the mechanical properties of materials for 3D printing using fused deposition modelling (FDM). As an illustration of the standard application, specimens were prepared for testing the tensile properties of plastic materials widely used in AM: PLA, PETG and ABS+.*

Keywords: *Additional manufacturing, AM, 3D printing, ISO, Fused deposition modelling, FDM, Tensile testing*

1. Introduction

The currently actual fourth industrial revolution is based on the concept and platform of digital manufacturing transformation - Industry 4.0. One of the nine pillars of the development and implementation of Industry 4.0 is Additive manufacturing (AM), also known as 3D printing. The very first 3D printing patent was about photopolymer rapid prototyping using UV radiation to material hardening and was registered in 1980 (Hideo Kodama). Fusion Deposition Modeling (FDM), today one of the most widespread AM processes, was patented in 1989 (Scott and Lisa Crump). As early as 2009, many companies are producing 3D printers that work on the principle of the FDM process and their price is rapidly decreasing, so now they have become available to every interested user, including home consumers [1]. AM is developing intensively nowadays and will be developing further in the future from all its aspects: technologies, processes, materials, software, equipment, postprocessing, quality management, market, etc. Therefore, there is an essential need for getting an order in this area, and this can only be achieved through standardization. The process of ISO standardization in this area has been going on for ten years and this is only beginning. When AM is used to create a model for a visual purpose (aesthetic design), the mechanical characteristics are not so important comparing to the external appearance, texture, colour, gloss, transparency, the accuracy of dimensions, shape and position. However, standardization is much more important in the field of functional 3D printing of end-use parts that have some function and accordingly must have the required mechanical properties. The paper [2] was published in 2015 and concerns the influence of layer thickness and raster angle on the mechanical properties of FDM 3D printed parts of ABS and PEEK materials. For the preparation of test specimens, as well as the tensile and compression test procedure, authors used the recommendations of Chinese national standards (GB standards). The applied standards are from 1996 and 2008, so it can be assumed that they do not refer to AM, but conventional technologies of plastic parts manufacturing and testing. The tensile test of ABS material used for FDM 3D printing to find the optimum building orientation that affects printed part strength is studied in paper [3]. For specimens preparation and testing, the authors refer directly to the conventional standards ASTM D638 (tensile test) and ASTM D695 (compression test), without mentioning at that time appropriate existing AM standards. A comparative analysis of the influence of layer height, infill density and layer orientation on the mechanical properties of PLA and ABS test specimens was carried out in paper [4]. In this study, the authors mention all relevant AM standards, as well as standards for conventional technologies, which AM standards refer to. The general and specific development of standardization in AM from the aspect of materials and technological approach is analyzed in [5]. The authors conclude that the current standard regulation in the field of AM is in an incomplete framework, but it is going in the right direction. The paper [5] is published recently and gives an excellent overview of the current state of AM standard regulations and provides some guidelines for the identification of appropriate standards.

2. Standardization in the field of AM

The Technical Committee ISO/TC 261 - Additive Manufacturing was created in 2011 and its secretariat is headed by the German Institute for Standardization - DIN (Deutsches Institut für Normung). This committee prepares standards in the field of AM technologies concerning terms and definitions, processes and process chains, procedures of testing, quality parameters, supply agreements etc. ISO/TC 261 has active participating members from 26 countries and 9 observer members. This committee is directly responsible for publishing 19 current AM standards. Also, 35 standards or draft standards in this area are currently under development and are expected to be published soon [6]. The ASTM (American Society for Testing and Materials) F42 committee for Additive Manufacturing Technologies was established in 2009 to promote knowledge, encourage research and implement technologies through the development of standards for AM technologies [7]. In 2011, ISO and ASTM signed a cooperation agreement to manage the ongoing joint efforts of the two organizations to jointly develop and adopt international standards that serve the global market in the field of AM. Therefore, some standards related to AM have ISO/ASTM designation. Three of the 19 published standards have ISO designation and refer to general principles (categories of AM processes and feedstock, main characteristics and appropriate testing methods) and laser sintering of thermoplastic materials. The other 16 standards have ISO/ASTM designation. These standards specify general principles (terminology, purchase requirements for AM parts); geometric capability of AM systems; material extrusion-based AM of plastic (feedstock, equipment); metal powders; design (requirements, guidelines and recommendations); laser-based powder bed fusion (metals, polymers); AM file format; coordinate systems and test methodologies; system performance, reliability and qualification principles for aerospace applications; data processing overview. The existence and availability of international standards in the field of AM are crucial for promoting the widespread use of AM processes and regulating the quality assessment of products made using AM technologies. The most important published ISO standards, developed under the responsibility of the ISO/TC 261 committee, concerning the topic and subject of this paper are [8-11]. In the absence of standards for testing materials that deal with materials and parts of AM, the existing current standards in the field of AM refer the user to the standards of testing the mechanical properties of materials for parts made by conventional technologies. In the case of plastic materials for FDM 3D printing, these are the standards [12,13].

3. Specimens preparation

3.1. Process

The AM process of Fused Deposition Modeling (FDM) was used to prepare the test specimens. This process is described in the “Material extrusion” section of Standard [10]. According to the standard definition, material extrusion is an AM process in which the material is selectively dispensed through a heated nozzle. Fusion is the process of uniting more units of molten material into a single unit of material. Other features are [10]:

- Feedstock: Filament, typically thermoplastics.
- Binding mechanism: thermal reaction bonding.
- Source of activation: heat.
- Secondary processing: removal of a support structure.

The standard [8] gives the overview of single-step AM processing principles for polymer materials used for FDM as follows:

- Type of material: Polymer.
- State of fusion: Thermal reaction bonding.
- Material feedstock: Filament material.
- Material distribution: Deposition nozzle.
- Basic AM principle: Extrusion of melted material.
- Process category: Material extrusion.

3.2. Material

For FDM 3D printing, bulk raw wire plastic material is used, specially intended for use in AM. The standard [11] considers only the term plastic, but not special types of plastic materials. For this study, the following materials were used: PLA, PETG and ABS+.

PLA (Polylactic Acid) is a biodegradable and bioactive thermoplastic polyester. The advantages of using this material are easy and fast printing, as well as relatively low printing temperature. Parts made of PLA have low load carrying capacity, low impact and heat resistance, low resistance to UV radiation. Due to the stated properties, this material is used more in aesthetic design than for mechanical needs. ABS+ (Acrylonitrile butadiene styrene) is a thermoplastic polymer most commonly used for 3D printing. The parts made of this plastic have high stiffness, impact and abrasion resistance. ABS+ plastic parts withstand higher temperatures (up to 100°C) without changing mechanical properties. However, this is a disadvantage for the printing process, because they require higher operating temperatures. They also absorb moisture from the air during printing. In general, the printing of parts made of ABS+ material is more complicated than the printing of other plastic materials, but parts made of this material have very good mechanical properties. PETG (Polyethylene Terephthalate Glycol) is a polyester, durable and easy to use. It has ABS+ mechanical properties and is easy to print like PLA. PETG plastic parts have high water-, chemical- and fatigue resistance. ABS+ and PETG are used for making functional parts, PLA is more used for applications without specific functional requirements.

3.3. Mechanical requirements

Standard [11] specifies basic quality properties of feedstock for AM and parts made by AM, appropriate test procedures and recommends the content of test agreements. The main quality properties of parts made using technologies of AM are: surface requirements (appearance, texture, colour); geometric requirements (dimensions, dimensional and geometrical tolerances); mechanical requirements (hardness, tensile strength, impact strength, compressive strength, flexural strength, fatigue strength, creep, ageing, frictional coefficient, shear resistance, crack propagation) and build material requirements (density, physical and physicochemical properties). The mechanical requirement for tensile strength is considered in this paper. Concerning tensile strength of plastic parts made by AM, standard [11] refers to a group of five standards ISO 527 for plastic products made by conventional technologies. For plastic parts manufactured using FDM technology, relevant ISO 527 standards are [12,13]. General principles for determining the tensile properties of plastics under defined conditions, methods, testing and controlling devices, conditioning, test procedures, as well as calculation, expression and reporting of test results are specified by [12].

3.4. Test specimen

Test specimen type 1A [13] (the specimen form preferred for directly-moulded multipurpose test specimens), is shown in Fig.1.

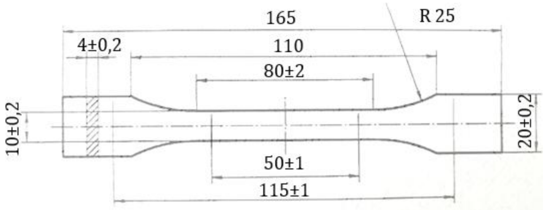


Fig. 1 *Specimen for standard tensile testing [?]*

3.5. Model preparation and 3D printer

The CAD model of specimens was created using SolidWorks 2018. Then the CAD model was converted to an STL (Stereolithography) file. After that, the model was prepared for 3D printing using Ultimaker Cura 4.6 software. The specimens were printed on a desktop FDM 3D printer (Ender 3 Creality), shown in Fig.2.

Fig. 2 *Ender 3 Creality 3D printer*

3.6. Printing parameters

The purpose of preparing specimens is their tensile strength testing depending on the material, infill density, infill pattern and orientation of the printed specimen in the build area. Other parameters of 3D printing are the same for all specimens, as it is shown in Table 1. There are currently no standard recommendations for these data and they have been selected empirically.

Table 1: *Unchangeable 3D printing parameters*

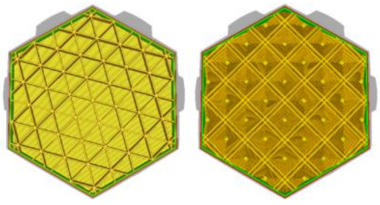
Layer height (Standard Quality	0.2 mm
Wall thickness	1.6 mm
Wall line count	4
Top/bottom thickness	0.8 mm
Top layer	6
Pring speed	50 mm/s
Wall speed	25 mm/s
Bottom layers	4
Initial layer height	0.3 mm
Wall speed	25 mm/s
Bottom layers	4
Initial layer height	0.3 mm

Variable printing parameters for prepared 53 different conditions are shown in Table 2. According to standard recommendations [12], a minimum of five test specimens shall be tested for each testing condition. Applied infill patterns (cubic and triangles) are shown in Fig.3. Different infill densities are shown in Fig.4. The printed specimen orientations in the build area are shown in Fig.5.

Table 2: *Variable 3D printing parameters*

PLA			
Printing bed temperature			50°C
Extruder temperature, from range (190…220)°C			200°C
No.	Infill pattern	Infill density, %	Orientation, °
1.1	Triangles	20	0
1.2	Triangles	60	0
1.3	Triangles	100	0
1.4	Cubic	20	0
1.5	Cubic	60	0
1.6	Triangles	20	90
1.7	Triangles	60	90
1.8	Triangles	100	90
1.9	Cubic	20	90
1.10	Cubic	60	90
1.11	Cubic	100	90
1.12	Triangles	20	45
1.13	Triangles	60	45
1.14	Triangles	100	45
1.15	Cubic	20	45
1.16	Cubic	60	45
1.17	Cubic	100	45
PETG			
Printing bed temperature			50°C
Extruder temperature, from range (230…250)°C			240°C
No.	Infill pattern	Infill density, %	Orientation, °
2.1	Triangles	20	0
2.2	Triangles	60	0
2.3	Triangles	100	0
2.4	Cubic	20	0
2.5	Cubic	60	0
2.6	Cubic	100	0
2.7	Triangles	20	90
2.8	Triangles	60	90
2.9	Triangles	100	90
2.10	Cubic	20	90
2.11	Cubic	60	90
2.12	Cubic	100	90
2.13	Triangles	20	45
2.14	Triangles	60	45
2.15	Triangles	100	45
2.16	Cubic	20	45
2.17	Cubic	60	45
2.18	Cubic	100	45
ABS+			
Printing bed temperature			100°C
Extruder temperature, from range (230…260)°C			245°C
No.	Infill pattern	Infill density, %	Orientation, °
3.1	Triangles	20	0
3.2	Triangles	60	0
3.3	Triangles	100	0
3.4	Cubic	20	0
3.5	Cubic	60	0
3.6	Cubic	100	0
3.7	Triangles	20	90
3.8	Triangles	60	90
3.9	Triangles	100	90
3.10	Cubic	20	90
3.11	Cubic	60	90
3.12	Cubic	100	90
3.13	Triangles	20	45
3.14	Triangles	60	45
3.15	Triangles	100	45
3.16	Cubic	20	45
3.17	Cubic	60	45
3.18	Cubic	100	45

For printing orientations of 45° and 90°, it was necessary to add support between the bottom of a printed specimen and the print bed. Orientation and location are defined in [15]. The standard [15], published in 2013, recently has been technically revised and will be replaced with its second edition which is currently under development (ISO/ASTM DIS 52921 *Additive manufacturing — General principles — Standard practice for part positioning, coordinates and orientation*).



Triangles Cubic

Fig. 3 *Infill patterns [14]*

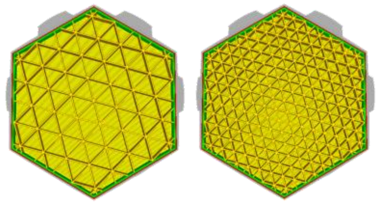


Fig. 4 *Different infill densities [14]*

0°

45°

90°

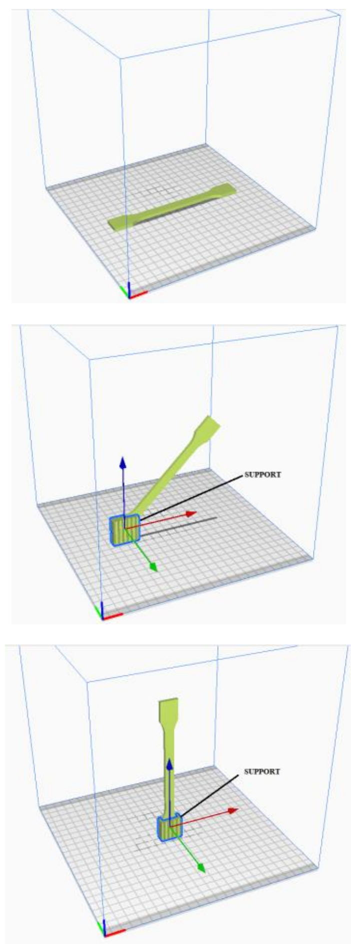


Fig. 5 *Specimen printing orientations*

The printed out specimens are shown in Fig.6. Since the specimen technical drawing contains some tolerated dimensions (Fig.1), these dimensions of the printed specimens were controlled and all of them are within the tolerance limits.

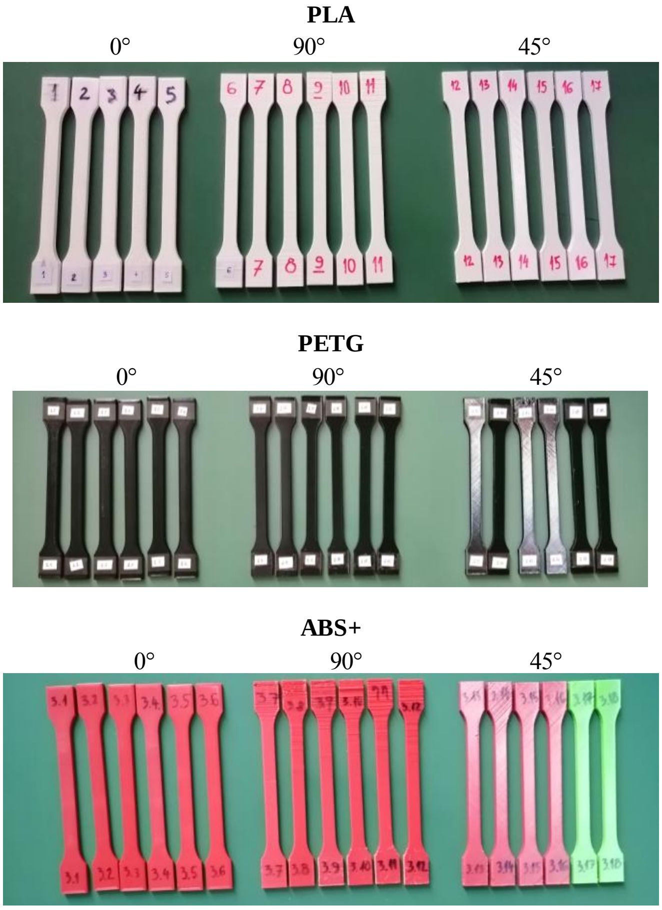


Fig. 6 *Groups of printed out specimens, depending on material and printing orientation*

As an example of a different appearance, the front side (see Fig. 6) of specimens made of different materials and printed with different orientations in the build area is shown in Fig. 7 (infill pattern and infill density are the same for all specimens - triangles and 100%). After preparing the specimens, a plan for tensile strength testing was made following the recommendations of the standards [12,13], concerning principles, methods, conditioning, procedure, calculation and expression of results and test report. The results will be the subject of future work and publications.

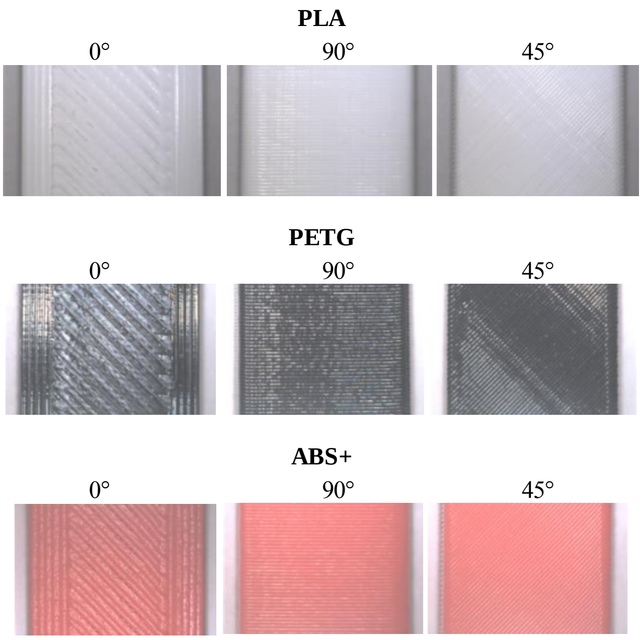


Fig. 7 *Specimen front side appearance depending on material and printing orientation (example of triangles infill pattern and 100% infill density)*

4. Conclusion

Based on the analysis of the current state of standardization in the field of additive manufacturing (AM) and on the example standard application for preparation of specimens made by using one of AM technologies - Fused Deposition Modeling (FDM) for mechanical tensile testing, the following can be concluded:

- AM technologies have existed and been continuously developed for 40 years;
- standardization in the field of AM lasts 10 years;
- 19 international standards (ISO and ISO/ASTM) considering different AM aspects have been published, and 35 ones are in the phase of adoption or development;
- due to the lack of intentionally developed standards especially for AM, manufacturers and users of AM products are referred to existing standards concerning conventional technologies (for example, AM standard ISO 17296-3 on main characteristics and corresponding test methods refers to 74 ISO standards listed in the bibliography);
- standards for conventional technologies cannot cover all aspects and specifics of AM, but in the intermediate period ISO recommends using these standards;
- research and practical experience in the field of AM show that the properties of 3D printed parts depend on many specific 3D printing parameters, which are not defined and described by current standards;
- carried out, published and scientifically validated research results, as well as practical experiences in the field of AM, significantly contribute to the development of AM theory and practice, as well as to the standard regulation in form of new standard recommendations respecting all the specifics of AM technologies.

5. References

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